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FATIGUE IN RIVETED AND BOLTED SINGLE LAP JOINTS

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STRUCTURAL DIVISION

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EXPLANATORY STATEMENT

Practices in the design of riveted and bolted joints have developed largely from experience and have not always been supported by conclusive experimental data. With this fact in mind, twelve sponsoring organizations instituted the Research Council on Riveted and Bolted Structural Joints, in 1947.

Important among the projects of the Research Council is the study of high-strength bolts in structural joints. The high-strength bolt is a comparatively new type of structural fastener, and its use combines the field economies of bolts with strength greater than that of rivets.

At the Centennial Convention of the ASCE at Chicago, Ill., in 1952, a group of papers were presented describing research that had been done in the field of structural joints, with particular emphasis on study of the high-strength bolt.

These papers are currently being published as Proceedings-Separates and will be distributed over a period of several months beginning in May, 1954. Later, they will be gathered to form a single symposium in the Transactions of the ASCE. The six papers in this group are as follows:

"The Work of the Research Council on Riveted and Bolted Joints," by W. C. Stewart;

"Laboratory Tests of High-Tensile Bolted Structural Joints," by W. H. Munse, J.M. ASCE, D. T. Wright, and N. M. Newmark, M. ASCE;

"Comparative Behavior of Bolted and Riveted Joints," by Frank Baron, M. ASCE, and Edward W. Larson, Jr., J.M. ASCE;

"Slip Under Static Loads of Joints With High-Tensile Bolts," by R. A. Hechtman, A.M. ASCE, D. R. Young, and A. G. Chin and E. R. Savikko, Junior Members, ASCE;

"Fatigue in Riveted and Bolted Single-Lap Joints," by J. W. Carter and K. H. Lenzen, Associate Members, ASCE, and L. T. Wyly, M. ASCE;

"Structural Application of High-Strength Bolts," by T. R. Higgins and E. J. Ruble, Members, ASCE."

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FATIGUE IN RIVETED AND BOLTED SINGLE LAP JOINTS

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SYNOPSIS

This paper presents a working hypothesis and orational explanation to explain the cause of and remedy for fatigue failures in structural joints, with supporting evidence. It also presents a correlation of recent fatigue test results on double lap joints made in the United States and attempts to show that these results are explained by this hypothesis.

INTRODUCTION

When studying new relations or phenomena only imperfectly understood the scientific procedure is to set up a working hypothesis which will take account of all the known facts, which will assist the investigator in evaluating the relations between new facts and facts already known, and which will assist in planning the search for new facts or relations. This hypothesis is modified when necessary to conform to these new facts.

Survey of Fatigue Failures in Structural Members

In 1947, at the request of American Railway Engineering Association Committee 15, the Association of American Railroads set up an investigation into the causes of and remedies for the fatigue failures in floor-beam hangers in railway bridges. This study, which has been conducted at the Purdue University Engineering Experiment Station, with the advice and assistance of the AAR Research Office, and supervised by an AREA Subcommittee, has consisted of a survey of the failures, field stress measurements on structures under service loads, laboratory studies under controlled conditions, and theoretical analyses. Significance is attached to the following facts yielded by the survey:

1. Some special circumstances or combination of circumstances must cause the failures since only about one out of six railroads report these failures, and only a few hangers develop failures in a given railroad.

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While the stress history of the members cannot definitely be established, investigation shows that the number of cycles of heavy loading has probably been less than 100,000 in most cases; axial and bending stresses have not been high, in some cases being quite low; the failures do not occur at points of greatest computed stress, and the range of stress has been relatively large, i. e., from 1 or 2 ksi to maximum tension stress.

3. With one or two exceptions, where vibration appears to control, the failures all occur thru the lowest rivet holes connecting the members to the gussets.
4. The failure cracks usually begin at the side of the rivet hole towards the toe of the hanger angle or channel at the point where the maximum tensile stress and strain concentration would be computed on the basis of elastic behavior, assuming the load to be delivered to the angle by rivet bearing.
5. While it is not possible to arrive at any exact knowledge either of the maximum stress or the state of stress preceding a failure crack in a given member the evidence shows clearly that the incidence of failure is increased by the presence of higher unit stresses.
6. These hanger failures all occurred in a single lap joints.* See Fig. A.
7. The working stresses to which these single lap connections had been subjected and which led to failures were much less than the fatigue strengths of double lap joints* reported by W. M. Wilson, Hon. M. ASCE, in Bulletin 302 of the University of Illinois Experiment Station in 1938.

Hypothesis

Consideration of the above facts led L. T. Wyly to formulate the following working hypothesis to explain the failures and to offer a proposed remedy;[1]

Working Hypothesis to Explain the Fatigue Failures in Hangers.

It is assumed that the index to the fatigue strength of a structural member is given by the magnitude of the tensile stress concentrations, computed on the elastic basis, and the total tensile strain concentrations, to which the member is repeatedly subjected.

The principal source of high stress and strain concentrations which result in the low fatigue strength of the hangers is the bearing of the rivets nearest the edge of the gussets in the holes at the failure section, probably acting in most cases with rivets which have lost or never had clamping force.

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*"Single lap" is a term commonly used in structural engineering to denote the type of joint shown on the right in Fig. 12.
"Double lap" denotes the type of joint shown on the left in the same figure. The latter is also called a "butt joint".

1. Report of Assignment 4. Stress Distribution in Bridge Frames — Floorbeam Hangers, by L. T. Wyly. Proc. AREA 1950, Vol. 51, pp. 498-9.

Proposed Remedy for Fatigue Failures

In the light of the above reasoning the remedy must lie in the elimination of bearing in the rivets at the edge of the gussets and the securing of high clamping force at these holes.

The natural solution for fatigue failures in riveted joints is the replacement of the rivets by non-bearing high strength high clamping bolts which will have ample initial clearance in the hole and hence will not bear on the plates, and to provide these bolts with a high clamping force to prevent slip and to provide an initial compression stress and strain at the sides of the holes.

The above explanation and proposed remedy was first presented to AREA Committee 15 at Purdue University on November 3, 1948, and subsequently, to the AREA Convention in March 1949. It was also presented to the American Institute of Steel Construction Engineering Conference in Chicago 1950.[2] Since the authors feel that the above explanation of the fatigue failures in riveted tension members and the remedy proposed have since been verified by studies by them and by others, and since they feel that the same explanation and remedy apply to double lap as well as to the single lap tension member connections and to beams with riveted cover plates, the remainder of this paper will be devoted to developing this thesis, with supporting evidence, in detail.

Supporting Evidence

Typical Fatigue Failures in Riveted and Bolted Structural Joints

Photos of typical failures in riveted and bolted structural joints are shown in Fig. 1. Where plates are connected by rivets or bolts acting in single shear and bearing and carrying little or no clamping the type of fatigue failure cracks shown in (a) and (b) may be expected. Where the plates are connected by high tensile bolts having no shear and bearing and transmitting load by friction resulting from high clamping, the type of fatigue cracks shown in (c) may be expected. The failures shown here were obtained in laboratory testing by Wyly and Carter. Examination of field failures in fatigue of riveted joints generally shows the type of cracks illustrated in (a) and (b).

Stress and Strain Concentrations at the Sides of Rivet or Bolt Hole in a Plate Carrying Axial Load.

It is pertinent to consider the stresses and strains existing at the sides of a rivet or bolt hole in a plate under increasing and repeated axial tension. Fig. 2 shows the measured tangential strains for such a test performed by Wyly and Carter in 1949. Fig. 3 compares the stresses computed for this test on the assumption of both unaxial and biaxial stress. Fig. 4 shows the tangential strain and stress concentration factors at the sides of the hole, using the strain and stress in the solid plate

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2. AISC Engineering Conference Proceedings 1950, April 12, Chicago, pp. 22-27 incl. Symposium on High Strength Bolts, Part 1, L. T. Wyly.

sections as the denominator. In Figs. 2 and 4 the ordinates are the average stress on the gross area of the bar.

The following facts are apparent:

1. The graphs of Fig. 2 bear a striking resemblance to the stress-strain graphs for the tensile tests of the material; the proportional limit and yield point are plainly evident, the plastic flow and strain hardening, overstrain, recovery of elasticity, the characteristic hysteresis loops, all are present.
2. After the material at the sides of the hole has been stressed well into the plastic range and allowed to rest, strain measurements, made by the authors but not given here, show that the material has recovered its elasticity.
3. In the region above the proportional limit, stresses shown by graph 1, of Fig. 3, computed from the unloading graphs of the hysteresis loops by using the product of E of 30,000 ksi times the elastic strains, are increasingly larger than the stresses of the tensile stress strain curve for a coupon test of the material, shown in graph 3, as the tensile load on both is increased.
4. Graph 1 of Fig. 3 resembles the lower stages of a true biaxial or triaxial tensile stress-strain curve for the material.
5. For comparison and study the stresses for a biaxial state of stress, i. e., for a condition of zero radial strain, in the material at the side of the hole, have been computed and shown in graph 2 of Fig. 3. Since the stress and strain under repeated loading are under consideration it seems reasonable to assume the values of Poisson's ratio shown in Fig. 3 in computing these stresses.

   It is not suggested that either graph 1 or graph 2 accurately represents the stress or the state of stress in the material at the sides of the hole. These graphs represent stress computed from the measured strains under certain simplifying assumptions and are presented to assist in studying these measurements. Measurements made by the authors, but not given here, indicate that, after unloading, residual elastic stresses are present and that elastic strains exist in the quantities labelled "plastic strains" in Fig. 2. These residual stresses have not been considered in computing the stresses for Graphs 1 and 2.
6. Fig. 4 shows tangential stress concentration values of about 3 for the stresses of graph 1 and a little more for the stresses of graph 2 in the material at the sides of the hole. This value remains nearly constant as the tension in the bar is increased. It is interesting to note that the value of k equal to 3.2 computed from the measured strains for biaxial stress in Fig. 4 agrees with the theoretical value for a specimen of the proportions tested.[3,4] The residual stresses noted above have not been considered in

3. Howland, R. C. J., On the Stresses in the Neighborhood of a Circular Hole in a Strip under Tension, Trans. Roy. Soc. London, Ser. A, Vol. 229, p. 49, 1929.
4. Wahl, A. M., and R. Beeuwkes, Stress Concentration Produced by Holes and Notches, Trans. Am. Soc. Mech. Engrs., Vol. 56, pp. 617-625, 1934.

computing the stress concentrations plotted in Fig. 4. The tangential strain concentrations in the material at the sides of the hole increase rapidly as the axial tension is increased, the maximum value measured in this test being about 14. At rupture of the material the value must be very large.

7. It seems likely that tangential strain concentrations at the sides of the hole act to open up and extend the infinitesimal crack or flaw in the material which is postulated in all fatigue failure theories and that this action increases with the magnitude of the strain concentrations, i. e., as the axial tension in the plate increases.
8. It seems likely that the stress and strain concentrations which occur at the root of the above infinitesimal crack develop in the same manner as the strain and stress concentrations measured at the side of the hole in Fig. 2, probably producing a brittle state of stress. When this stress reaches the true tensile strength of the material the latter pulls apart and crack propagation has begun.
9. The fatigue strength of the plate should vary inversely with stress and strain concentrations and hence inversely with stress on the gross area as long as the stress at the side of the hole does not reach the elastic limit of the material. The fatigue strength of the plate should decrease rapidly as stress in the plate producing tangential stress above the yield point at the side of the hole is raised.
10. The above facts assist in explaining the influence of so-called "stress raisers", i. e., notches, holes, corrosion pits, etc., in lowering fatigue strength of ductile material.

The outstanding feature of the graphs of Fig. 2 is the magnitude of the elastic strain developed for a given total strain in the material at the side of the hole.

The behavior of this material is undoubtedly explained in large part by the reinforcing effect of the material in the plate immediately behind and integral with the thin section which carries the high local stresses. This situation is analogous to the case of a steel beam stressed above the elastic limit on the extreme fiber. Since this over stressed material is reinforced, and only limited plastic flow is permitted, by the elastic material immediately adjacent towards the neutral axis, no sudden and large deflection will occur until all parts of the beam have reached the plastic state in bending.

The restraining action of the elastic material of the plate permits only very small increments of straining to occur during a given time in the highly stressed thin section at the side of the hole. When the stress in the thin layer of steel at the side of the hole reaches the yield point, at a strain in the neighborhood of .001 in. per in., flow occurs, as Fig. 2 shows. This flow is limited by the restraint of the next adjacent layer which is still elastic. As additional tension is added to the plate the next adjacent layer stretches elastically, the first layer taking no additional stress at this stage, and the additional strain measured in the strain gage on the first layer is due to elastic stretch in this second layer. When the yield point in this second layer is reached it in turn

will flow and again will be restrained by the third layer, the strain measured in the gage on the first layer being always influenced by the restraining layers of material.

It is possible that some radial stress, or some normal stress, or both, may also act on the material in question. The adjacent elastic material may restrict the contraction in a normal direction as the material stretches in a tangential direction.

There is no stress radial to the surface of the material at the sides of the hole. However, a very small depth below this surface there is such a radial stress in tension. It is possible that this stress acts to reduce the strains at the sides of the hole somewhat. It is also possible that under these restrained flow conditions the rise in Poisson's ratio from the elastic value of about .25 or .30 to the plastic value of about .50 may take place gradually. This would also affect relations between stress and observed strains.

Where a notch is substituted for a hole as the strain and stress raiser, the build-up of the radial tensile stress just below the surface at the root of the notch is quite substanial and develops quickly. A very clear picture of this has been given by Professor Maxwell Gensamer.[5]

The spreading of the plastic region around the hole in a tension member is very clearly described by Nadai in both text and figures.[5a]

The proportionality between fatigue strength and stress concentrations in the member for values of the latter up to about 3 has long been recognized. The experimental determination of the stress concentration by comparative fatigue tests for stresses within the elastic limit rests upon this proportionality.[6] Fig. 5 illustrates this relation also. The stress concentrations in each of the five holes in line in the steel plate were measured experimentally. The plate was then tested in the fatigue machine and failure by progressive brittle fracture occurred through one of the end holes where stress concentration was greatest.

Stress and Strain Concentrations at the Sides of a Rivet Hole Due to Bearing of the Rivet on the Plate Material.

When a load is delivered to the plate through bearing of a rivet on the material around the hole, the tangential stress and strain concentrations are about 6 or about twice as large as in the former case; and the location of the maximum stress at the side of the hole is above the center of the hole toward the bearing side, a distance of about a sixth of the diameter. These facts are shown in Fig. 6. The photoelastic measurements by E. O. Stitz,* and the steel plate measurements by J. W. Carter check and supplement each other.

In a single lap joint the effect of the bearing of the rivet on the edge of the contact face of the plate when slip occurs, as shown in Fig. 7B

* Professor of engineering mechanics at Purdue University.

5. Strength and Ductility, by Maxwell Gensamer. Transactions of Am. Soc. for Metals, 1946, Fig. 19, p. 55.

5a. Theory of Flow and Fracture of Solids, by A. Nadai, Esq., Vol. 1, 2nd. Edition, McGraw-Hill, pp. 289-296, Figs. 18-32 to 18-45 inclusive.

6. See for example: "Stress-concentration Factor Found From Repeated Stress Tests", p. 292-4. Resistance of Materials by Fred B. Seely, 3rd. Ed., Wiley.

(b), is to produce a magnification of the stress and strain concentration at the side of the hole.

Overload and Bearing Stress in End Rivets

It has been shown by M. B. Scott**A.M. ASCE, J. M. Durfee***, and R. M. Stone***Jun. M. ASCE, in tests of a double lap tension joint having a single line of rivets, that at working loads the rivets at the end of the splice or gusset plates are overloaded about 100 percent or more, that the inside rivets take very little load and that slip of the end rivets may occur at working loads. See Fig. 9.[7,8,9] Previous studies by others had demonstrated the same overloading of the end rivets.[10,11]

Exploratory Laboratory Fatigue Tests

Attention is now directed to Fig. 7A, B which summarizes the results of exploratory fatigue tests by Wyly and Carter made to check the above working hypothesis and proposed remedy. Note that all stresses are computed on the gross section. This seems to the authors to be desirable since it provides a common denominator to use for all cases. However, the same tests are shown with the stresses given on the net section for comparison in Figure 8.

For repeated stresses acting in tension only the result of all fatigue tests of riveted and bolted structural joints for a given grade of steel, when plotted in S-N diagram form, should fall between two boundary curves: an upper curve Study A, representing the fatigue strength of plain structural steel plates having no holes, and a lower curve Study 1, representing the fatigue strength of a single lap joint connected by bolts having no clamping force and transmitting loads by shear and bearing only. This is tantamount to saying that the most unfavorable stress and strain concentrations at the sides of the holes will be caused by loads delivered in rivet bearing with no clamping present and that the most favorable stress and strain concentrations at the sides of the holes will be caused by high clamping without any bearing stress. Exceptions will occur if lateral bending, poor holes, or other unusual stress-raising factors, are present which may lower the fatigue strength of the lower curve. Examples of such exceptions are given later in the paper.

For structural carbon steel the upper boundary curve discussed above is given by the tests performed by W. M. Wilson, on plates without

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7. Fig. 23, p. 492, Proc. AREA 1950.
8. An Investigation of the Effect of Clamping Force on Load Distribution in a Single Line Riveted and Bolted Butt Joint. Master's Thesis, by J. M. Durfee, 1950. Purdue University.
9. Investigation of the Load Distribution in a Single Line Riveted and Bolted Butt Joint. Master's Thesis, by R. M. Stone, 1950. Purdue University.
10. Tests of Large Riveted Joints, by Davis, Woodruff, and Davis. Fig. 13, and pp. 1222-1225 incl. Trans. ASCE 1940.
11. Discussion by Hill and Holt on "Work of Rivets in Riveted Joints", Table 5, p. 467, Trans. ASCE, 1934.

holes[12] and on a standard I beam without cover plates.[13] These results are shown as Study A, in Fig. 7A.

For structural steel having a yield point of about 32 ksi a lower boundary curve has been obtained by Wyly and Carter and is shown as Study No. 1 in Fig. 7A.[14, 15] In this series the holes were bored and the bolts were turned to a push fit in the holes. The nuts were turned on by the fingers only and held in place with cotters; no clamping was used. The endurance limit for these conditions was found to be 16 ksi on the net area or about 12.5 ksi on the gross area. Since the stress and strain raising effect on the beam flange of the rivets in bearing at the end of a partial length cover plate should be about the same as the stress and strain raising effect on the hanger material of the rivets in bearing at the end of the hanger gusset plate, the same fatigue strength should be expected of each. It is significant that the S-N curve showing the fatigue strength of standard I beams with partial length cover plates obtained by Professor W. M. Wilson, Study B in Figs. 7A and 10,[16] agrees very closely with the Study 1 curve for a single lap joint. The added fatigue strength due to rivet clamping may explain the fact that the beam tests show a little greater strength than the bolted joints in Study 1. It is equally significant that, with one exception, the failures in Professor Wilson's beams all occurred, not at the point of greatest bending stress, i. e., at the center of the span and under the load, but through the rivet hole at the end of the cover plate.

Conversely, when the bearing stress is eliminated and bolts with high clamping are used instead of rivets, the fatigue strength rises immediately. The S-N curve Study 2 was obtained by Wyly and Carter for such connections, using the same steel as for Study 1. The endurance limit found here was 24 ksi on the net area or about 18.7 ksi on the gross area.[17,18] In this case the failure was by brittle progressive fracture with the cracks originating not at the edge of the holes, but in the center of the main plate under the washer at the edge of the bolt head or nut where the tension at the plate surface due to clamping would be large[19,20]

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12. Fatigue Strength of Riveted Joints, by W. M. Wilson, Table 37, p. 100, Bull. 302, University of Illinois Eng. Exp. Sta., 1938.
13. Flexural Fatigue Strength of Steel Beams, by W. M. Wilson, Table 3, p. 13. Bull. 377, University of Illinois Eng. Exp. Sta., Jan. 22, 1948.
14. Progress Report presented to AREA Committee 15, by L. T. Wyly and J. W. Carter, Oct. 17, 1951.
15. Fatigue Tests of Single Lap Joints. Fig. 23, p. 64, AREA Bull. 502, June-July 1952, by Wyly and Carter.
16. Table 14, Bull. 377, p. 24, University of Illinois, Eng. Exp. Sta. Jan. 22, 1948.
17. Progress Report to AREA Committee 15, by Wyly and Carter, Oct. 26, 1949.
18. Exploratory Fatigue Tests, by Wyly and Carter. Fig. 24, p. 493, Proc. AREA 1950.
19. Exploratory Fatigue Tests, by Wyly and Carter, p. 499, Proc. AREA 1950.
20. Stress Concentrations in Built-up Structural Members, by J. W. Carter. AREA Bull. 495, 1951. p. 1.

In these tests, the washers were smaller than required by specifications subsequently adopted and were undoubtedly too thin, resulting in higher stresses at the point of failure than are desirable or necessary. For the single test labeled "2A", the clamping force was less than for the tests plotted in Study 2 curve. The 17 percent increase in fatigue strength is in the right direction. It is probable that with the proper design of washers, the S-N curve for the single lap non-bearing, high clamping joint would be raised still closer to the S-N curve for solid plates without holes, Study A. Whether it can be raised as high as the Study A is still to be determined. In fact, broadly stated, the answer to this question may be said to be the main objective of further work in this field.

To further demonstrate the beneficial effect of eliminating rivet bearing and adding high clamping, and also to demonstrate that the same factors control the fatigue strength both of beams with cover plates and of single lap joints, the test of a 10" wide flange beam with partial length cover plates connected by high tensile bolts was made. See Fig. 7A Study 3 and Fig. 10. After stressing to an extreme fiber unit stress of 21,500 psi on the gross section or 28,600 psi on the net section at the end of the cover plates for 5 million cycles;[21] no slip had occurred and no failure had occurred and the test was stopped. In this test the washers used conformed to the present specifications recommended by the Research Council for Riveted and Bolted Structural Joints. Again it seems highly probable that considerably greater stresses could have been used on this beam with the bolted cover plates without incurring failure.

Where severe initial stresses or strains at the rivet holes or initial cracks in the steel, etc., may be present, the fatigue strength of a riveted joint could be expected to fall considerably below the S-N curve Study 1. Such a test result is shown in Study 4, Fig. 7A.[22] Here the 1 inch bored holes in the plate and gusset were held off center by 1/32 inch and a polished drift pin of the same diameter as the hole held normal to the plates was forced through the hole, thus stretching the metal at the sides of the rivet hole. This joint was then tested at a maximum stress of 14,000 psi on the gross section (18,000 psi on the net section) in repeated tension. Failure occurred by brittle progressive fracture after about 70,000 cycles of loading. It seems probable some such circumstances as this drifting operation, perhaps combined with rivets with low clamping, may have been present in some of the relatively few floorbeam hangers with riveted connections which have failed in fatigue, while it was not present in the case of the many other hangers which have not failed.

A different result was obtained when the polished drift pin 1 inch diameter was forced through a bored hole 31/32 inch diameter in a single plate, thus enlarging its diameter all around. The results of this cold working operation were:

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21. Progress Report to AREA Committee 15 and to Research Council on Riveted and Bolted Structural Joints, by L. T. Wyly and J. W. Carter, Feb. 15, 1952.
22. Progress Report presented to AREA Committee 15, by L. T. Wyly and J. W. Carter, Oct. 17, 1951.

1. To stretch the metal above its elastic limit in tension around the circumference of the hole i. e., in a tangential direction.
2. To compress the metal beyond its elastic limit in a direction radial from the center of the hole at the same time.
3. To leave residual compressive tangential stresses in the material when the adjacent metal contracted elastically as the pin was removed.

Fatigue tests were run on two such identical specimens. Each was subjected to a tension loading cycle of 1 ksi to 18 ksi on the net section of the plate for over 4 million repetitions of load. No signs of failure occurred in either case.

Two factors enter into this test. The cold working of the metal included not only stretching around the circumference, but also compression at right angles to the circumference. This operation was thus similar to the refining action of cold drawing a wire through a die. This would not be expected to open up existing minute cracks. Secondly, the residual compressive stresses act to hold together any minute cracks in the metal and also to reduce the magnitude of tensile stresses during later fatigue loading. Both of these effects have long been recognized as acting to increase fatigue strength of metal.

These tests are plotted as Study 5 in Fig. 7A.

The correlation of stress concentration with fatigue failures in structural members has been investigated by J. W. Carter by means of photoelastic studies of plastic models of riveted joints* and also by measurements on steel models.[23] He found that the failure cracks through the rivet holes, both at points of initiation and during subsequent propagation, coincide almost exactly with the maximum tensile stress locations and paths in the material on a section through the rivet holes as computed on the basis of elastic behavior and assuming the load to be delivered to the plate by rivet bearing.[24] See Fig. 11. In fact, a fatigue crack of the type shown in Fig. 1 (a), (b), and Fig. 11, (b) originating at the side of the rivet or bolt hole a distance of about one-sixth of the diameter away from the transverse diameter towards the bearing side of the hole, and following the trajectory of the principal tensile stress, may be taken as prima-facie evidence that the crack has been initiated by rivet- or bolt-bearing.

Using specimens having about the proportions of usual riveted joints, he also studied the stress distributions and measured the critical stresses at the sides of the hole for: a single lap joint having a rivet in bearing but with no clamping; a plate under clamping without axial load, and with axial load; and the stress at the top of the plate under the washer at the outside edge of the bearing surface of the bolt head due to clamping without axial load, and with axial load as listed in Table 1.

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* Mr. Carter's polarized light studies for this project, which were part of his doctoral thesis, were performed under the direction of Professor E. O. Stitz.

23. Stress Concentrations in Built-up Structural Members, by J. W. Carter. AREA Bull. 495, 1951.

24. Progress Report to AREA Committee 15, by J. W. Carter. May 2, 1951.

Table 1

LIST OF CARTER'S PHOTOELASTIC STUDIES

Case	Joint	Location of Measured Stresses	Rivet Bearing	Clamping Force	Axial Load	Fig.	AREA Bull. 495 Reference Sec.	Page
a-a	Single lap	Sides of hole Tangential tension	Full	None	Full	12*		22
b.	Plate with washers	Sides of hole Tangential compression	None	Full	None	13(b)	A-A	24
c.	Plate with washers	Sides of hole Normal compression	None	Full	None	13(c)		25
d.	Plate with washers	Top of plate under edge of washer	None	Full	None	13(d)	A-A	25
e.	Plate with washers	Sect. through plate under washer	None	Full	None	14	A-A	27
b-a	Plate with washers	Sides of hole Tangential tension and compression	None	Full	Full	15	B-B	29
d-a	Plate with washers	Top of plate under edge of washer	None	Full	Full	15	A-A	29

*See also Table 1, page 23 of AREA Bull. 495

It should be noted that the experiments shown in Figs. 13, 14, and 15 represent the case of a bolt head bearing on a plate without any intervening washer, i. e., the proportions of the washers shown in these figures correspond to those of the bearing surface of a bolt head, and the load was distributed over the washer as nearly uniformly as was practicable. In these experiments the computed average stress under the washer due to clamping was about two and a half times the axial stress on the gross section.

These measurements showed the following:

1. Very high tensile tangential stress concentrations existed at the sides of the holes at the surface of the plate in contact with the gusset in a single lap joint when rivet bearing without clamping occurs under axial loads. See Fig. 12.
2. With bearing removed and clamping added the stress distribution changed in character and in magnitude. Without axial load on the

specimen the stress distribution at the side of the hole was tangential compression across the thickness of the plate; the magnitude varying from 22 to 38 percent of the average compression between the washer and the plate. See Fig. 13 (b). The addition of an axial load equal to 40 percent of the average compression exerted by the washer on the plate reduced this tangential stress at the surface of the plate to near zero and changed the stress at the center of the plate to tension about equal to the axial stress. See Fig. 15 (a).

3. With clamping present the tensile stress concentration at the face of the plate under the carburized washer at the edge of the bearing surface of the bolt head was equal to or greater than the average compression between the washer and the plate and the stress gradient was very sharp at this point, probably denoting a state of stress approaching brittleness. See Figs. 13 (c) and 14. When axial load was added to the specimen the above tensile stress concentration in the face of the plate at the edge of the washer was increased by an amount about equal to the added axial unit stress. See Fig. 15 (b).

It is believed that these measurements of stress provide a reliable index to the location and magnitude of the stress and strain concentrations that exist at the points in the joint where fatigue failures occur. Furthermore, they show that clamping force has a dual role. It not only builds up frictional resistance to sliding on the contact planes of the joint; a function formerly assigned to rivets in shear. It is also an indispensable agent whose operation determines the magnitude and character of the stress and strain concentrations at the bolt or rivet holes. It makes all the difference between a connection having rivet- or bolt-bearing, high tangential stress and strain concentrations, and low fatigue strength, and a connection having no rivet- or bolt-bearing, favorable stress and strain distributions and high fatigue strength.

These measurements also explain the manner of failure of the plates at the high tensile bolted joints, where cracks start at the top of the plate under the edge of the bearing surface of the bolt head. They also suggest that by proper washer design, i. e., by reducing the sharp and severe stress and strain concentration and the sharp stress gradient, this type of failure may be brought under control.

The measurements in Figs. 13 (d) and 15 also suggest that further studies of the effect of clamping upon local stress distribution are desirable. Variables studied should include plate thickness and any possibility of a brittle state of stress resulting. This should include impact tests.

Slip and Clamping Force

The critical requirement in the case of the high tensile bolt for structural connections is the ability to develop and hold indefinitely a high clamping force and to resist slip indefinitely.

The first conclusive demonstration that a structural joint, designed to fail in the plates, connected by high tensile bolts, and depending on

friction at the contact faces alone to prevent slip, can be used to carry a large number of repetitions of load, was made by K. H. Lenzen early in 1947 in carrying out a test program set up by the American Institute of Bolt, Nut and Rivet Manufacturers* with the late Professor G. A. Maney, M. ASCE, at Northwestern University.[25] This series of tests of 9 double lap joints, connected by 8 or 9 high tensile bolts, carried a reversed stress of from plus and minus 15 ksi to plus and minus 20 ksi on the net section for a total of 325,000 to 1,600,000 cycles, without slip prior to failure. This series included:

1. The development of the carburized washer which is necessary to enable high clamping to be built up and which has since been standard equipment with the high tensile bolt for structural work.
2. The carrying of the clamping force in the bolts into the yield strength range without serious loss of clamping.
3. The measurement of normal compression stress in the metal at the sides of the hole due to clamping under varying amounts of axial load in the plate.[26]
4. Measurement of the clamping force in the bolts during the test and computation of an average coefficient of friction between the contact surfaces of the plates of .35 or .36 at time of the first major slip in static test.

Professor Maney had measured the axial and shearing stresses in bolts due to torqueing and found the latter to be a small percentage of the total stress.[27] Lenzen found that when a high tensile bolt is unloaded and reloaded by torqueing, the shear stress rises rapidly due to the galling which occurs in the threads.

In 1949 Wyly and Carter completed the tests in tension of 7 single lap joints connected with high tensile bolts comprising Study 2 of Figs. 7A and 8. Loading was at the rate of 1,000 cycles per minute, and the maximum number of cycles carried was 7 million. No measurable slip occurred in these tests. These bolts also were torqued into the yield stress range.[28]

Fatigue Strength and State of Stress

Lenzen performed another series of fatigue tests which illustrate the effect of state and magnitude of local stress upon fatigue strength of a riveted and bolted joint.[29] Four double lap specimens were tested in which the connection consisted of four high tensile bolts spaced about

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* Now the Industrial Fasteners Institute

25. The Effect of Various Fasteners on the Fatigue Strength of a Structural Joint, by Kenneth H. Lenzen, AREA Bull. 480, June-July, 1949.
26. Bolt Stress Measurements by Electrical Strain Gages, by G. A. Maney. "Fasteners," Vol. 2, No. 1, p. 10.
27. Same as Ref. 25, Figs. 9 to 12 incl.
28. Progress Report to AREA Committee 15, by L. T. Wyly and J. W. Carter, October 26, 1949.
29. Same as Ref. 25, Fig. 22, Table 6, pp. 23f.

equally each way in two transverse rows of two holes each. In the center of the bar, in each row, an open hole was placed. This arrangement thus secured four corner holes where the tangential stresses were in initial compression under the bolt clamping and two open holes where tangential stress and strain concentration due to the presence of the hole would be expected under axial loading. All four joints failed by cracks originating at a transverse diameter of the open hole in the center of the main plate on the most heavily stressed side. These cracks spread to the edges of the plate, passing outside the bolt holes and through the point under the edge of the head or nut of the bolt where the tension and stress gradient in the surface of the plate would be highest. This is to say that the failure cracks originated at the point of greatest tensile stress and strain concentration (the sides of the open hole) and followed the path of highest tensile stress and strain to the edge of the plate. This is what might be expected from Carter's model study of stress concentration as shown in Figs. 11, 13 (b) and 15 (a).

While the scope of this paper is limited to the study of causes of fatigue failures in riveted and bolted joints directly attributable to the connection details, it is well to remember that stress raisers from other sources may very markedly reduce the fatigue strength of such members. Tension members in pin-connected spans have been characterized traditionally by ragged cuts and sharp copes near the joints. It is noteworthy that the axial unit stresses producing failure in the hangers of the pin-connected spans are about 4 ksi. to 6 ksi. lower than the axial unit stresses which produced failures in the riveted spans. This lower fatigue strength may be directly attributed to the presence of these large stress raisers in the pin-connected hangers. It is also especially notable that the more severe the stress raiser the lower the fatigue strength.[30]

In Lenzen's series of nine joints fabricated with cold-driven rivets, two specimens (C-6 and C-7) failed through the main plate outside the connection, the cracks in each case starting through a flaw in the edge of the plate due to flame cutting.[31] Also, four of the other joints in this series developed low fatigue strength apparently due to slippage and eccentricities arising from the unequal filling of holes and low clamping strength in this type of connector.

It should be borne in mind that the fatigue failures which were studied in the railway bridge floorbeam hangers and in the tests plotted in Studies 1 to 5 incl., in Figs. 7A and 8, occurred in members subjected to a minimum of bending due to eccentricity of loading or to lack of lateral bracing. Fig. A shows the typical make up and connection of the hangers to the upper gussets where failures mostly occur. The connection consists of two single lap joints, one on each flange, the eccentricities of which balance each other. The plates of Studies 1,

30. Report of Assignment 4. Stress Distribution in Bridge Frames — Floorbeam Hangers, by L. T. Wyly. Proc. AREA 1950, Vol. 51, pp. 479, 494-5. Figs. 17 to 21, incl.
31. Same as Reference 25, Fig. 18, Table 4.

2, 4 and 5 were tested in stiff holders and likewise suffered little bending from eccentricity or lack of bracing. The cover plates of Study 3 were fastened to the beam flange. The effect of the bending due to the above causes would logically be to reduce the fatigue strength below the results shown in Figs. 7A and 8. An example of this action is shown by the report of tests or specimens AMS BMS and CMS in the paper in this symposium: "Laboratory Tests — High Tensile Bolted Structural Joints" by W. H. Munse, J.M. ASCE, D. T. Wright, J.M. ASCE and N. M. Newmark, M. ASCE. These tests were conducted to study this particular question.

CORRELATION OF FATIGUE TEST RESULTS FROM VARIOUS SOURCES — DOUBLE LAP JOINTS

The result of some 150 fatigue tests from the sources listed in the figure are plotted in Fig. 16 for comparative study. The specimens were all double lap joints, and were tested on zero to maximum tension fatigue cycles. Stresses are given on the net sections as shown in the sources. Failures shown are as defined in the reports. The upper and lower boundary curves are those given in Figs. 7A and 8. The individual points for these boundary curves are not plotted here. The outstanding conclusions are:

1. All the test results lie between the upper and lower boundary curves established in Figs. 7A and 8 except where the bearing stress of the rivets was 5 times the tensile stress in the plate.
2. The fatigue strength of double lap riveted joints may be as low as the lower boundary curve Study 1 established for single lap joints if the rivet bearing stress is high enough. See tests* from Source 3 where rivet bearing was from 2.5 to 3.8 times the tensile stress. When the bearing stress is raised to 5 times the tensile stress the fatigue strength of such joints even falls below the lower boundary curve, Study 1. See tests from Source 1, Table 35, 36.
3. Under favorable conditions of high clamping and low bearing and low shear the double lap riveted joint may attain a fatigue strength equal to the upper boundary curve Study A. See Joints B 13-1 and B 14-1 tested at 35,000 psi and B 14-3 tested at 30,000 psi, all from Source 1, Table 22, p. 79.
4. The fatigue strength of double lap riveted joints appears to decrease as the bearing increases, and to increase as the clamping force increases. Since the clamping force is usally assumed to increase with grip, the high fatigue strength of the joints B34, B35, B36, from Source 1, Table 22, p. 79 with 3" grip, even with fairly high bearing, may be explained. However, there is no assurance that a long grip will always develop high clamping force and therefore high fatigue strength. The A3H joints from Source 4, tested at 28,000 psi, approach the lower boundary curve, Study 1. See Table 13.

* HF 1, Table 2, p. 22, HGFI Table 5 p. 34, HGGFI Table 6 p. 35, HF 2, Table 8, p. 52.

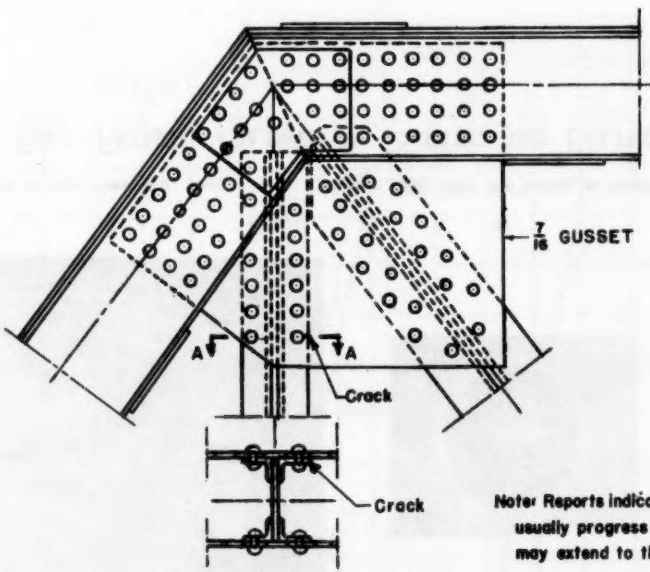
5. The double lap bolted joints with high clamping force and no bearing may develop a fatigue strength equal to the upper boundary curve Study A. It is noteworthy, however, that only a few of these specimens did reach this high strength. The evidence seems to indicate that the clamping force used in the tests of Table 24 of Source 1 was not high and in addition the bolts were not made of high strength steel. The report for Source 4 states that for most of the specimens the torques used to obtain clamping force were lower than present specifications require and the bolts were in bearing after the first application of load.
6. The spread of test results for the fatigue tests of the riveted joints is so great as to raise the question of whether rivets should be depended upon under repeated loads to develop fatigue strength above the lower boundary curve of Study 1.

The results of this correlation tend to support the working hypothesis and proposed remedies outlined in Fig. 7.

ACKNOWLEDGMENTS

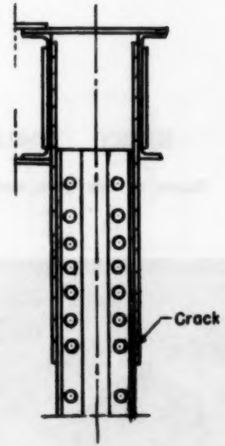
The authors are indebted to the Association of American Railroads and the Research Council for Riveted and Bolted Structural Joints for permission to publish the data given in this paper. Thanks are due to the American Railway Engineering Association for permission to produce Figs. 5, 6, 11, 12, 13, 14, 15, which appeared in J. W. Carter's paper, "Stress Concentrations of Built-Up Structural Members," in AREA Bulletin 495, June-July 1951, and Fig. 9 which appeared as Fig. 23, p. 24 in the Assignment 4 in AREA Bulletin 485, Jan. 1950. The specimens and holders for the fatigue tests performed at Purdue University were generously donated by the Wisconsin Bridge and Iron Company of Milwaukee, Wisconsin. The writers are indebted to Professor E. O. Stitz for valuable advice and suggestions.

The tests reported in Figs. 2, 3, and 4 are part of a research project sponsored by the Research Council for Riveted and Bolted Structural Joints. The other tests reported are part of the floorbeam hanger project sponsored by the Association of American Railroads. Both projects are being conducted at the Purdue University Engineering Experiment Station under the direction of L. T. Wyly. Administration is by Professor R. B. Wiley, head of the School of Civil Engineering and Engineering Mechanics, and by the director of the Engineering Experiment Station and dean of engineering. Dr. A. A. Potter retired as director of the Engineering Experiment Station and dean of engineering in June 1953, and has been succeeded by Dr. G. A. Hawkins.



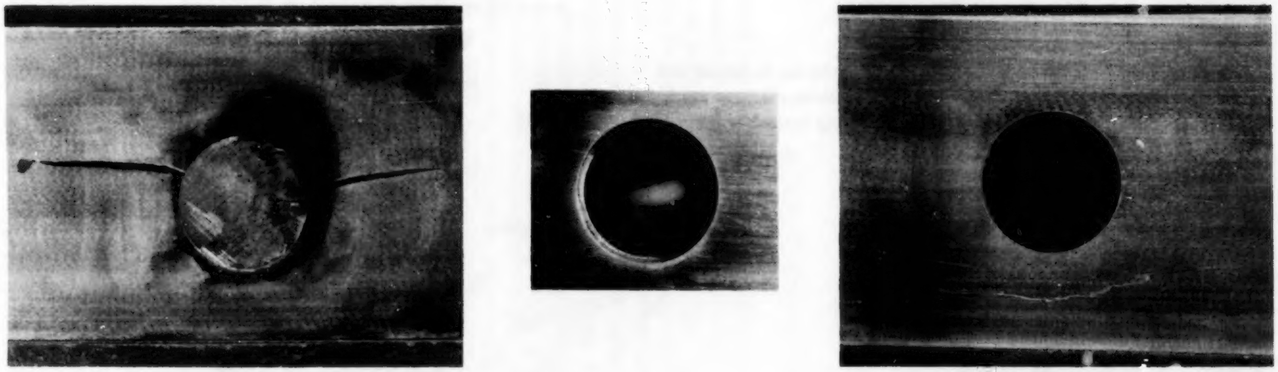
SECTION A-A

Note: The cracks start in any one of the four angles of the hanger.



Note: Reports indicate that cracks start at side of rivet hole, and usually progress toward edge of angle first, and subsequently may extend to the back of the angle.

FIG. A
TYPICAL FAILURE SECTION
120'-0 RIVETED THRU TRUSS SPAN
22 FAILURES IN 15 IDENTICAL SPANS



(a) Rivets in single shear and bearing.

(b) Bolts in single shear and bearing, no clamping.

(c) High tensile bolts no bearing.

FIG. 1 - FATIGUE FAILURES IN RIVETED AND BOLTED STRUCTURAL JOINTS

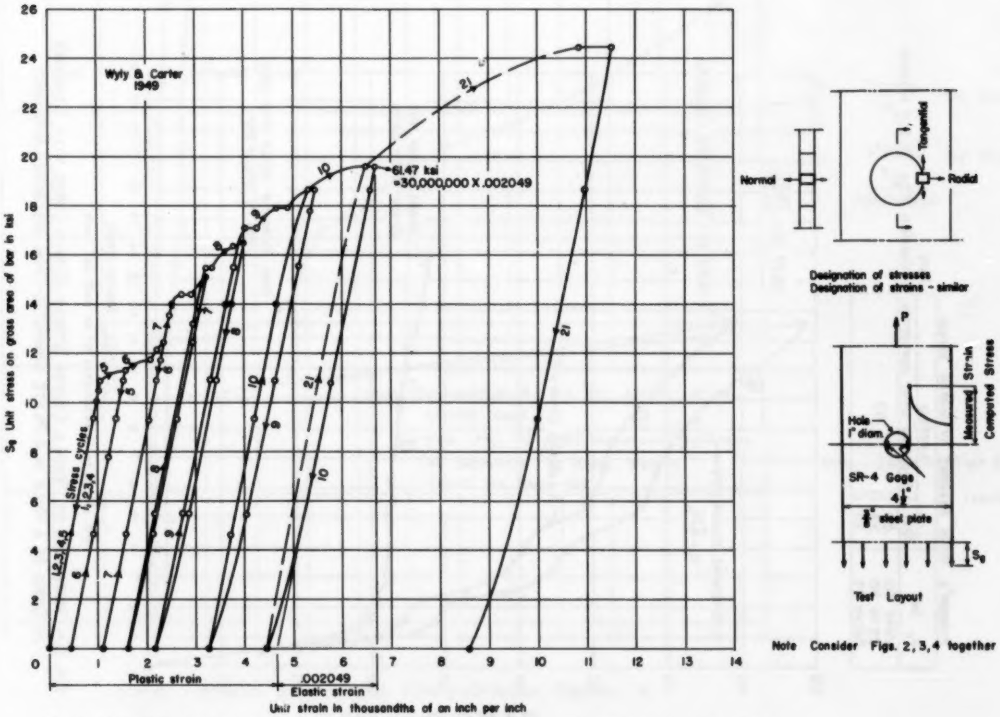


FIG. 2 MEASURED STRAINS AT THE SIDES OF A HOLE IN A PLATE UNDER INCREASING AXIAL TENSION

Poisson's Ratio Assumed for Biaxial Stress

S_2 ksi	Loading: First	Loading: Repeated after overstrain
Above 30	.50	.33
25 to 30	.33	
Below 25	.30	

Note
Consider Figs. 2, 3, 4 together

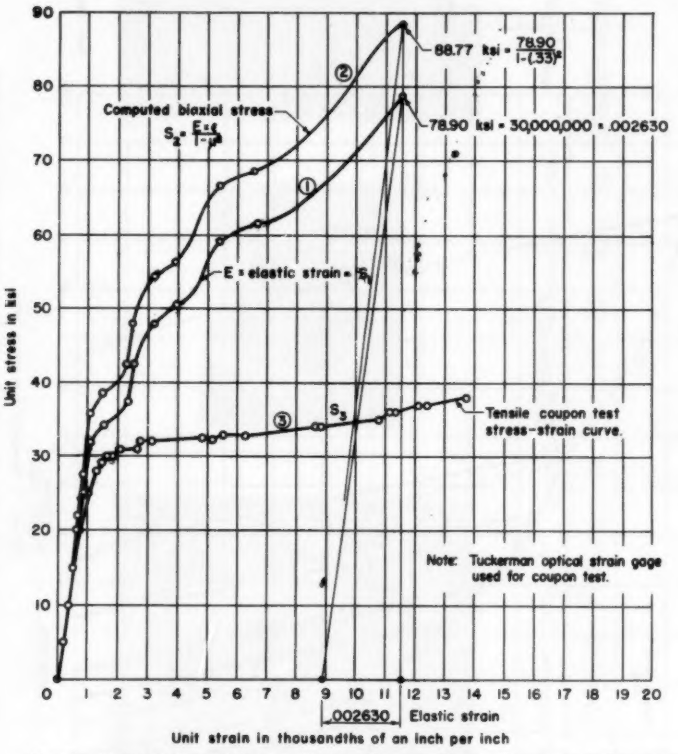
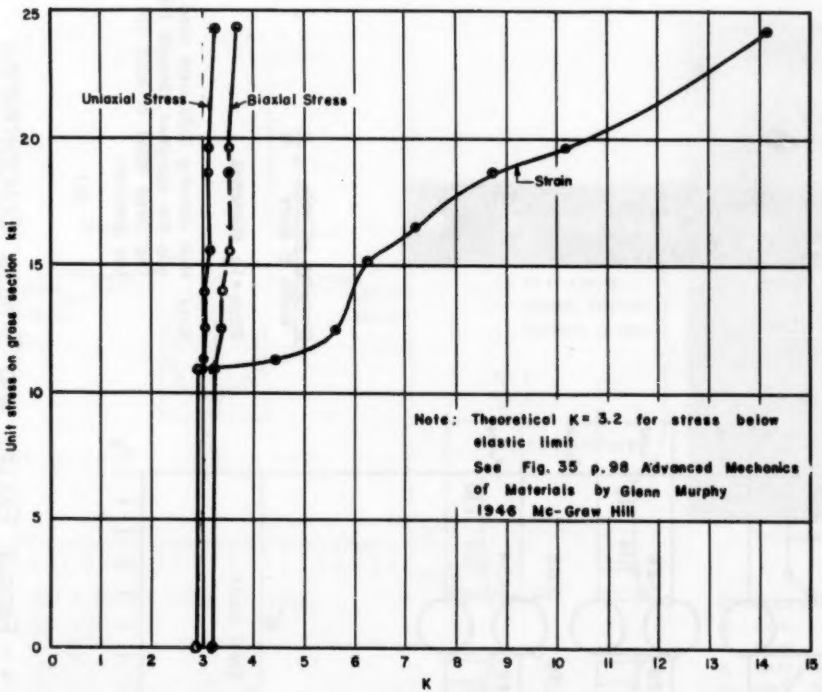


FIG. 3.— COMPARISON OF TENSILE COUPON STRESS-STRAIN CURVE WITH STRESSES AT SIDES OF A HOLE IN A PLATE COMPUTED FROM MEASURED STRAINS



$$K = \frac{\text{Stress}}{S_g} \quad \text{for Stress}$$

$$K = \frac{\frac{\text{Strain}}{S_g}}{30000000} \quad \text{for Strain}$$

Note Consider Figs. 2, 3, 4 together

FIG. 4 STRESS AND STRAIN CONCENTRATION FACTOR K FOR TEST OF FIG. 2

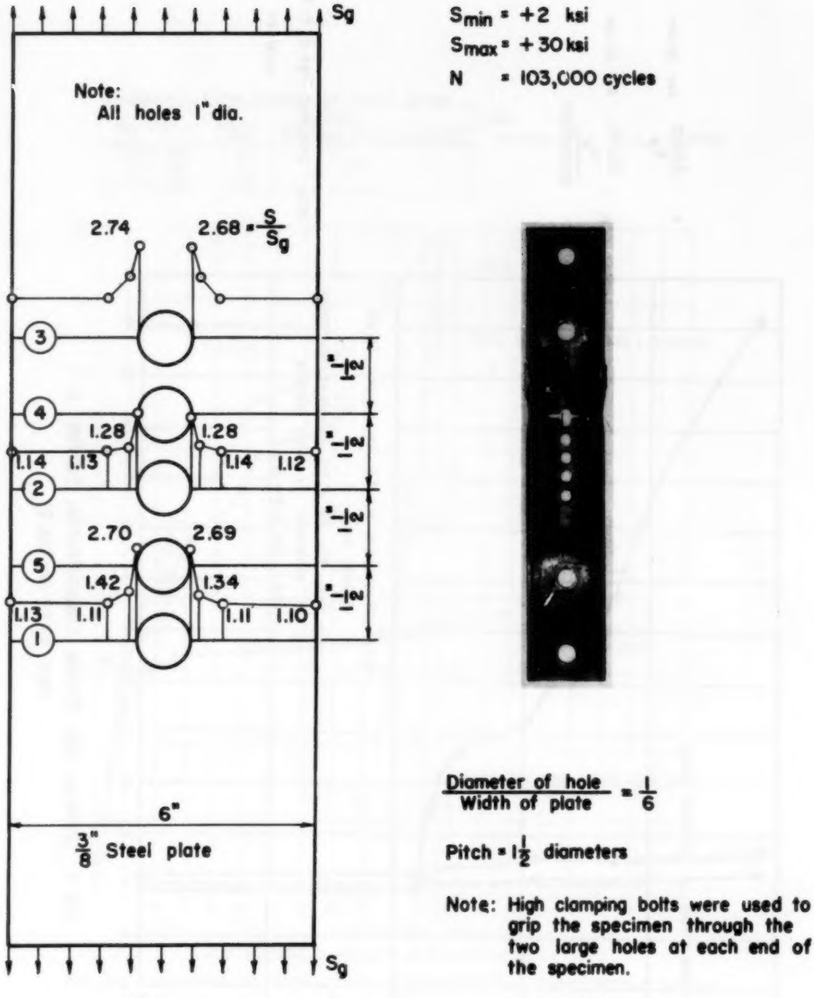
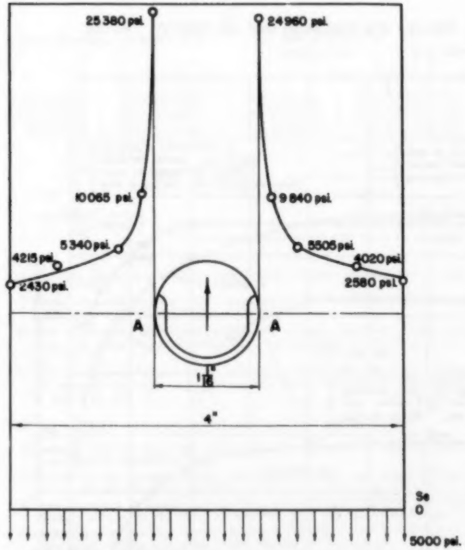


FIG. 5 – FATIGUE FAILURE AND STRESS CONCENTRATION



SR-4 STRAIN GAGES ON STEEL

$\frac{d}{W} = 0.236$

$S_e = 5000$ psi J.W. CARTER JANUARY 1948

$S_A = 25\,380$ psi.

$\frac{S_A}{S_e} = 5.10$ (a)

$S = \frac{2nf}{t}$

n = No. OF FRINGES

f = MATERIAL CONSTANT

t = THICKNESS OF MODEL

$n_A = 9$

$n_B = 11$

$f = 1.95$

MATERIAL : FOSTERITE

FRINGE PHOTO BY E.O. STITZ

PHOTOELASTICITY

$\frac{d}{W} = 0.236$

$S_e = 21.1$ psi. NOVEMBER 1948

$S_A = 106$ psi ; $S_B = 134$ psi.

$\frac{S_A}{S_e} = 5.03$; $\frac{S_B}{S_e} = 6.25$ (b)

FIG. 6

CORRELATION BETWEEN STRESSES FROM PHOTOELASTICITY AND SR-4 STRAIN GAGES

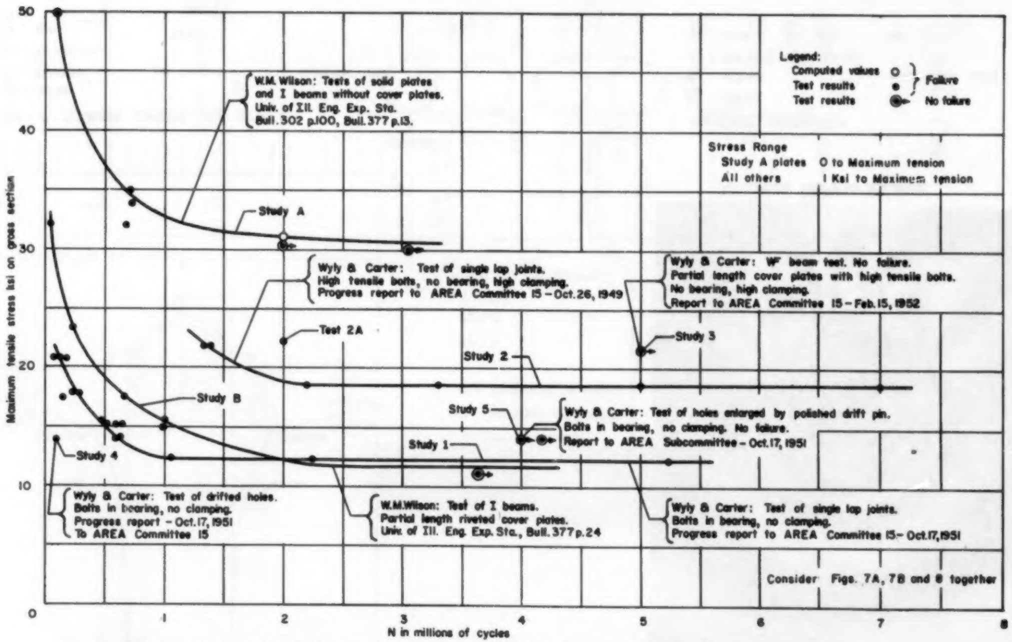
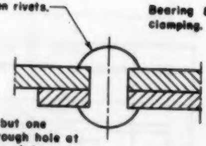


FIG. 7A CAUSES OF AND REMEDIES FOR FATIGUE FAILURE IN RIVETED AND BOLTED SINGLE LAP JOINTS

(a) Before loading

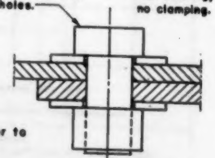
(b) After loading

Eccentric bearing of end rivet on plate in lap joint



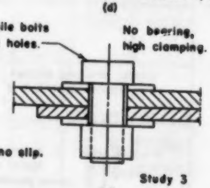
All failures but one occurred through hole at end of cover plate.

(c) Study 8



No slip prior to fracture.

(d) Studies 1,4,5



No failure, no slip.

(e) Study 3

Note Connections for Studies 2,2A similar except 1" bolts used

Connections for Studies 1 to 5 incl.

CAUSE: High stress and strain concentrations at sides of holes due to high rivet bearing plus low clamping.

1. Plates slip under working loads, especially at end rivets, and when clamping force is low. End rivets are overloaded. See (b) and Fig. 9.
2. With low clamping large rivet bearing sets up high stress and strain concentrations at sides of holes. For single lap joints these concentrations are very high at the edge of the contact plane of the plate. See (b) and Fig. 12
3. With low clamping force, a range of stress in the member will produce a magnified range of stress and strain at the sides of the holes and will lower the fatigue strength of the member. See Figs. 1,2,3,4,12 and Studies 1, 8 and A of Fig. 7A.

REMEDY: Eliminate rivet bearing and provide a high clamping force.

1. Replace rivets by bolts and provide enough clearance so that the bolt will not bear on plate in the hole under service loads. See (e).
2. Provide a high clamping force in the bolt to prevent slip under service loads and to prevent high stress and strain concentrations at the sides of the hole. See Fig. 13(a),(b),(c) and Fig. 15(b).
3. Provide design of washer adequate to reduce tensile stresses and strains in plate from clamping so that fatigue failures in the plate outside the hole will be avoided. See Figs. 13(d) and 14.
4. Avoid local stress and strain raisers in the holes due to drifting or other damage. See Fig. 7A, Study 4. Also avoid notches and other stress raisers in fabrication.
5. With the high tensile stress and strain concentrations at the sides of the hole due to the bolt and to rivet bearing eliminated by high clamping, and with the high tensile stress and strain concentrations in the face of the plate under the washer due to high clamping reduced, the fatigue strength of the plate will approach the fatigue strength of a solid plate with no holes. See Fig. 7A, Studies 2,2A,3.

Note: Consider Figs. 7A, 7B and 8 together

FIG. 7B – CAUSES OF AND REMEDIES FOR FATIGUE FAILURE IN RIVETED AND BOLTED SINGLE LAP JOINTS

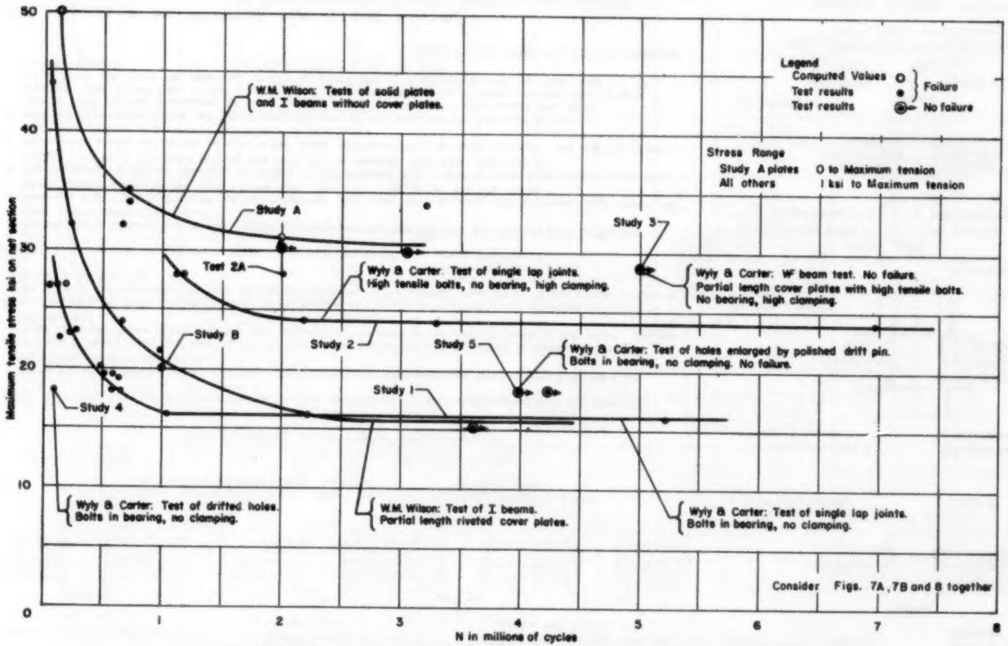


FIG. 8 - STUDIES 1 TO 5, A, & B, OF FIG. 1 - STRESSES ON NET SECTION

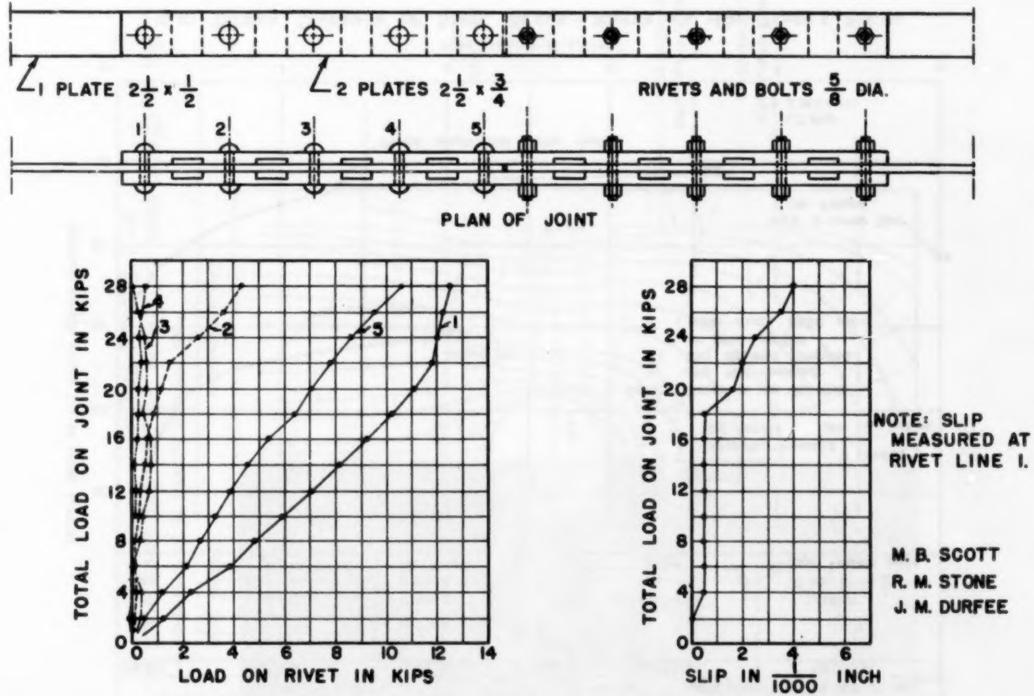


FIG. 9 LOAD DISTRIBUTION IN BUTT RIVETED JOINT

Nov. 1948

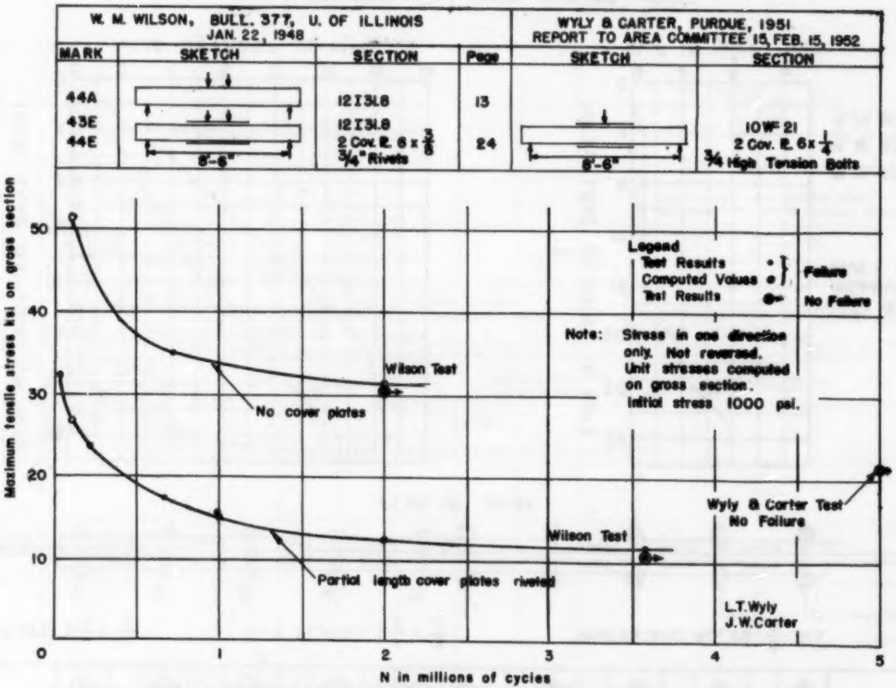


FIG. 10 - FATIGUE STRENGTH OF STEEL BEAMS — RIVETS VS. HIGH TENSILE BOLTS

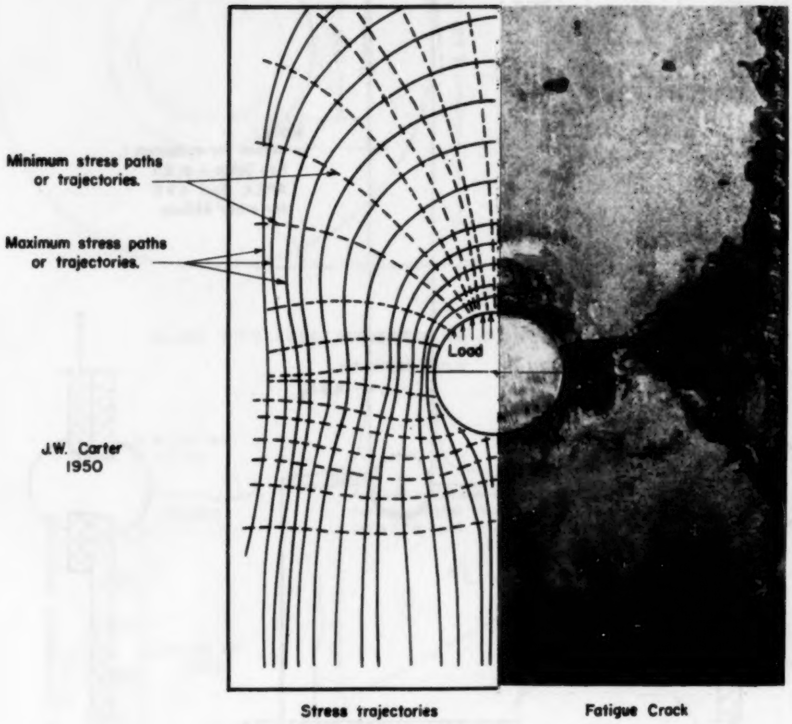


Plate with load delivered by pin in bearing

FIG. 11 - CORRELATION OF STRESS VALUES AND DIRECTIONS WITH FATIGUE FAILURE

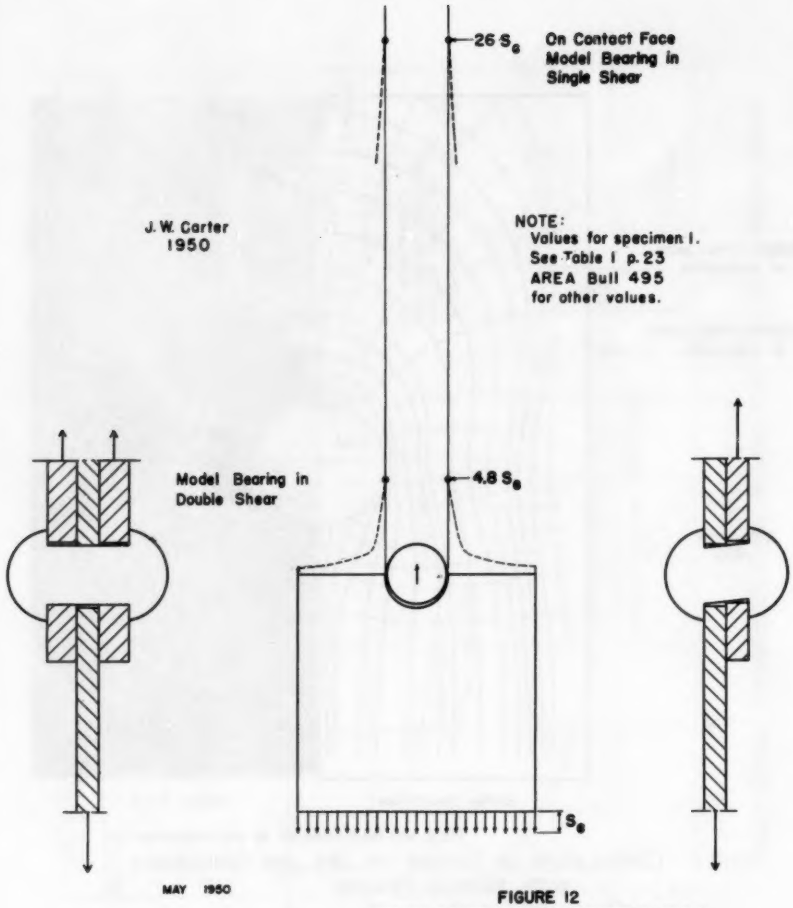


FIGURE 12
STRESS CONCENTRATION AT SIDES OF HOLE
DUE TO
RIVET BEARING

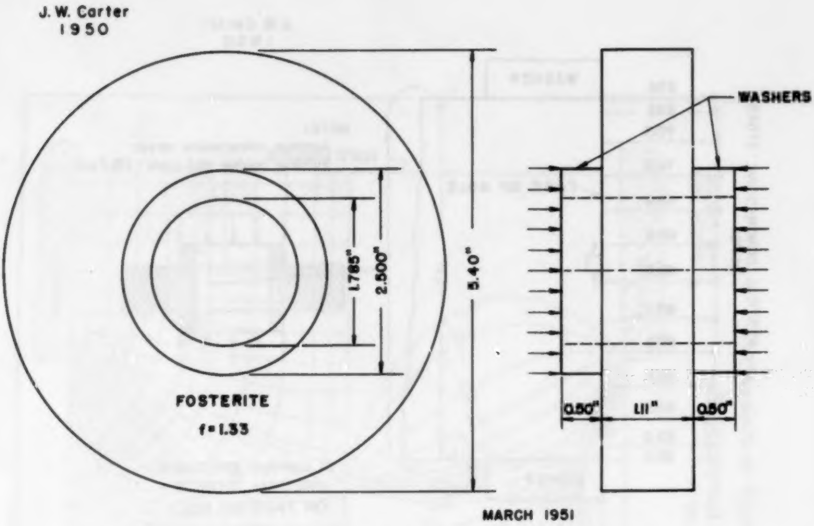
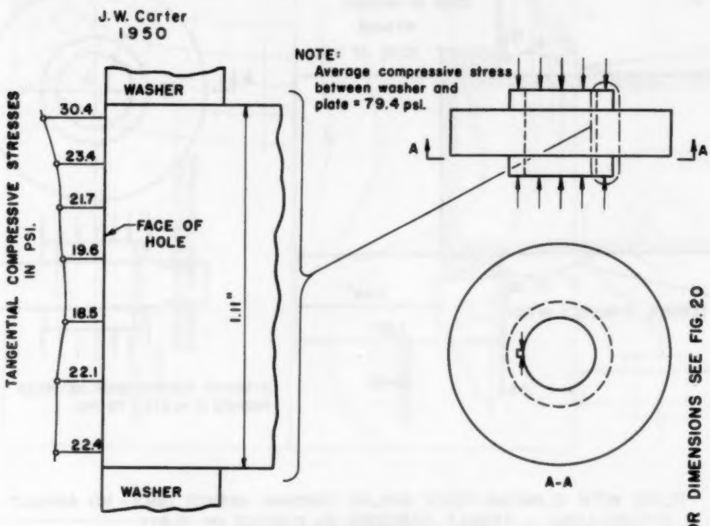


PLATE WITH HOLE SUBJECTED TO CLAMPING FORCE OF WASHERS ONLY

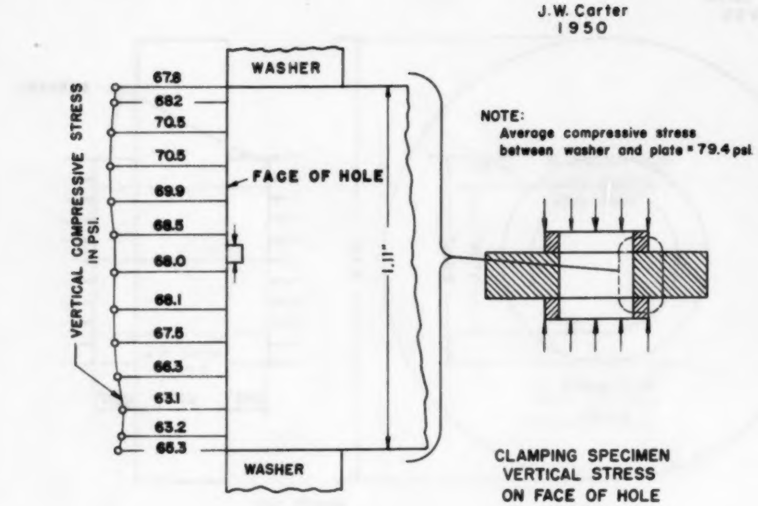
(a)



CLAMPING SPECIMEN
TANGENTIAL STRESS ON FACE OF HOLE

(b)

FIG. 13 - STRESS DISTRIBUTION DUE TO CLAMPING



CLAMPING SPECIMEN
VERTICAL STRESS
ON FACE OF HOLE
(c)

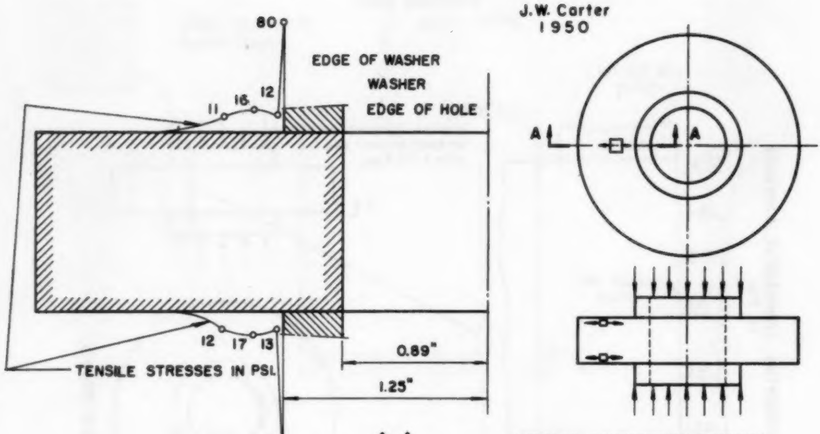


PLATE WITH CLAMPING FORCE APPLIED THROUGH WASHER ONLY - NO AXIALLY APPLIED LOAD - TENSILE STRESSES ON SURFACE OF PLATE

(d)

FIG. 13—STRESS DISTRIBUTION DUE TO CLAMPING COMPLETED

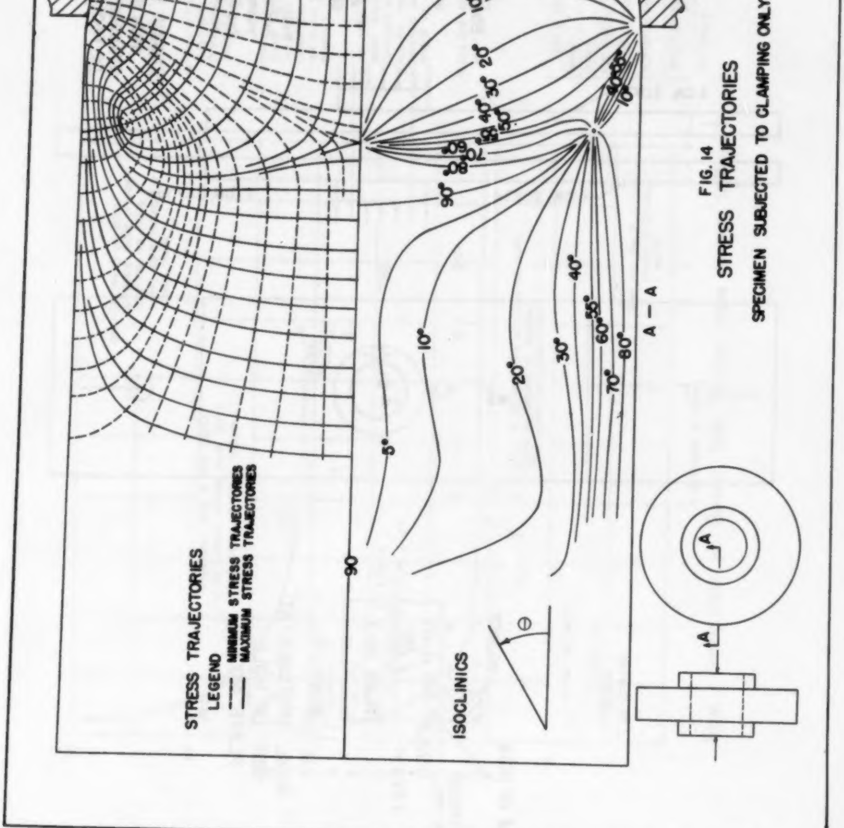
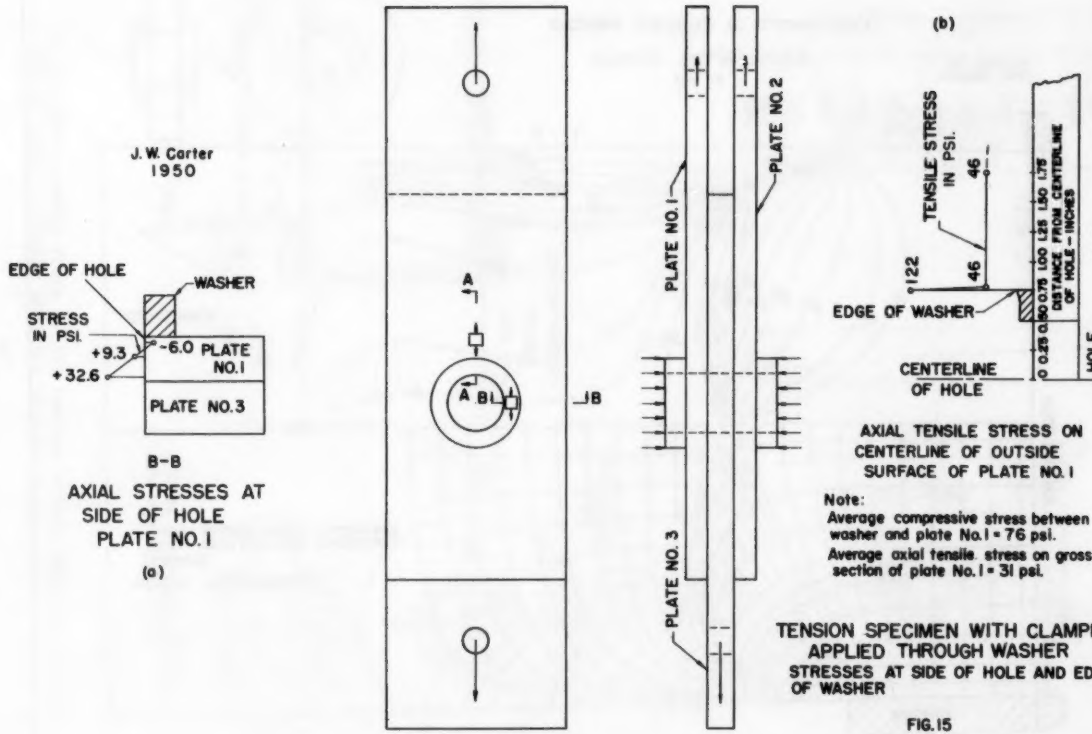


FIG. 14
STRESS TRAJECTORIES
SPECIMEN SUBJECTED TO CLAMPING ONLY



AXIAL STRESSES AT SIDE OF HOLE PLATE NO. 1

(a)

AXIAL TENSILE STRESS ON CENTERLINE OF OUTSIDE SURFACE OF PLATE NO. 1

Note:
Average compressive stress between washer and plate No. 1 = 76 psi.
Average axial tensile stress on gross section of plate No. 1 = 31 psi.

TENSION SPECIMEN WITH CLAMPING APPLIED THROUGH WASHER
STRESSES AT SIDE OF HOLE AND EDGE OF WASHER

FIG. 15

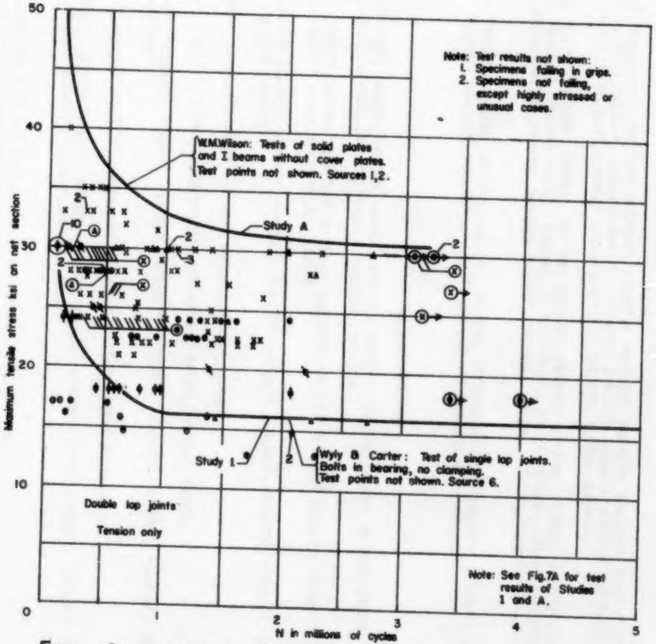


FIG.16 —CORRELATION OF FATIGUE TEST RESULTS FROM VARIOUS SOURCES

Sources of data shown

1. Bull. 302 Univ. of Ill. Eng. Exp. Sta. - 1938 by W.M.Wilson and Frank P. Thomas.

2. Bull. 377 Univ. of Ill. Eng. Exp. Sta. - 1948 by W.M.Wilson.

3. Tests of Riveted Joints with High Rivet Bearing Aug.1, 1948 Progress Report. Committee on Project 1 Research Council for Riveted and Bolted Structural Joints.
by Wilbur M. Wilson and William H. Munse.

4. Results of Static and Fatigue Tests of Riveted and Bolted Joints Having Different Lengths of Grip. Jan.2, 1952. Conducted at Northwestern Univ. in Cooperation with the Research Council for Riveted and Bolted Structural Joints.
Project V.
by Frank Baron and Edward W. Larson Jr.

5. The Effect of Certain Rivet Patterns on Fatigue and Static Strengths of Joints. Feb. 1, 1952. Conducted at Northwestern Univ. in Cooperation with the Research Council for Riveted and Bolted Structural Joints.
Project VII
by Frank Baron and Edward W. Larson Jr.

6. Bull. 502 AREA, Fatigue Test of Single Lap Joints. June - July, 1952 ; Fig.23, p.64.
by L.T.Wyly and J.W.Carter.

Legend

Type of joint	Symbol	Source	Table
Bolted		1	24
Bolted	▲	4	13
High bearing rivets	♦	3	2, 3,6,8,10
Cold driven rivets	●	4	13
Hot driven rivets	x	1	21,22,26,28
		4,5	13,16
Very high Bear. Rivs.	O	1	35,36
No failure	O→		

PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

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a. Presented at the New York (N.Y.) Convention of the Society in October, 1953.
b. Beginning with "Proceedings-Separate No. 290," published in October, 1953, an automatic distribution of papers was inaugurated, as outlined in "Civil Engineering," June, 1953, page 66.
c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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